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CORNING GLASS WORKS

ELECTRO-OPTICS LABORATORY

RALEIGH, NORTH CAROLINA

IMPROVED SCREEN FOR REAR PROJECTION VIEWERS

Technical Report No. - 8

Date - March 8, 1966

Period Covered - February 8, 1966
to
March 8, 1966

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TECHNICAL REPORT #8

I. Theoretical Studies (Mie Scattering)

Theoretical investigations of light scattering by particles with sizes comparable with the wavelength of illumination is continuing. Light scattering data have been computed for particle sizes of $\alpha = 1$, 2, 3, 4, and 5 ($\alpha = \frac{\pi D}{\lambda}$ where D is particle diameter) for $m = .90$ and 1.05 and from $\alpha = .2$ to 5.0 in steps of .2 for $m = 1.20$. Figures 1, 2, and 3 show theoretical angular gain characteristics of several different screen materials. Each figure is for a single relative index of refraction between the particles and the surrounding medium (m). The family of curves in each figure represent different particle sizes. Although data for 20 individual curves in Figure 3 were computed only 5 data are shown because of the slow change of the shape of the curves with changing α. It can be seen by comparing the curves of equal α, in the three figures, that they are almost identical. Thus it may be possible to use an empirical equation which has the same general shape as the data and gives a good fit to it, using empirically determined constants along with the size parameter α. Such an approach will be tried.

Figure 4 gives the gain at $\theta = 0$ vs. the size parameter α. Here the data from Figures 1-3 are plotted together. For the most part, the data corresponding to different refractive indexes cannot be separated enough to show any significant differences over the ranges of particle sizes covered. This however, is not the case for large α. Similarly the curves of Figure 5 of efficiency vs. α, and Figure 6, of

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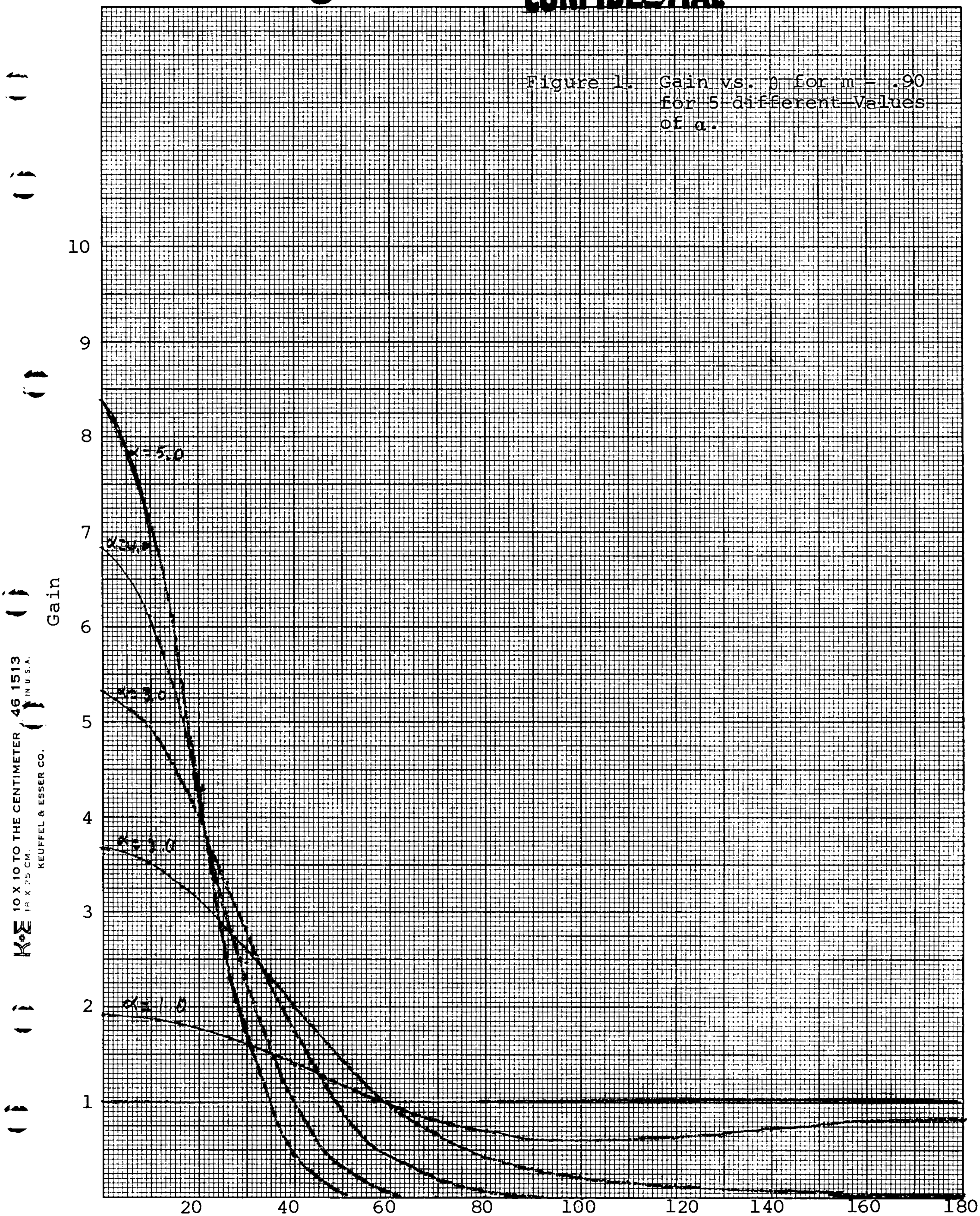

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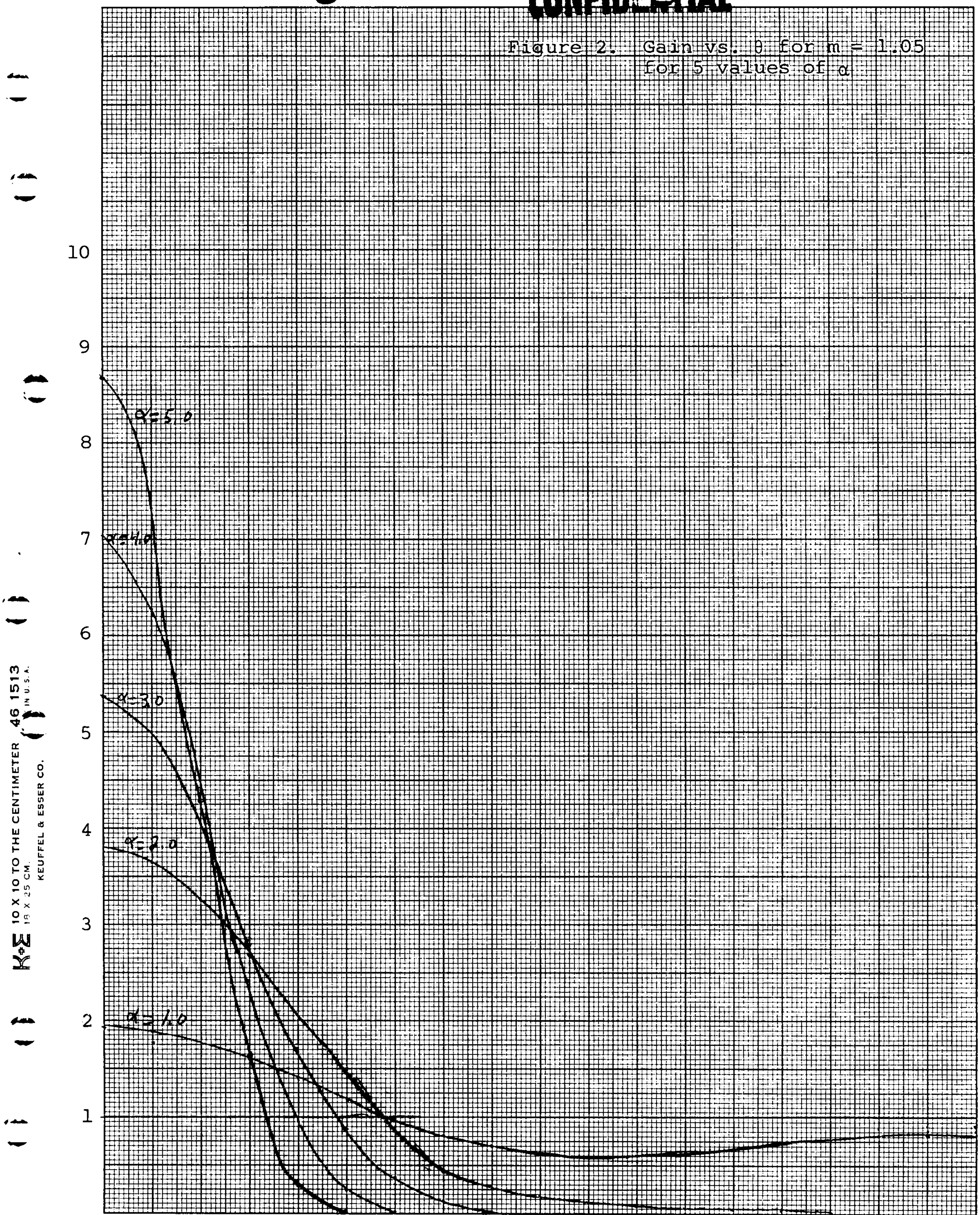

Figure 2. Gain vs. θ for m = 1.05
for 5 values of α
α=5.0
α=4.0
α=3.0
α=2.0
α=1.0
10
9
8
7
6
5
4
3
2
1
20
40
60
80
100
120
140
160
180
10 X 10 TO THE CENTIMETER 46 1513
18 X 25 CM.
KEUFFEL & ESSER CO.
MADE IN U.S.A.

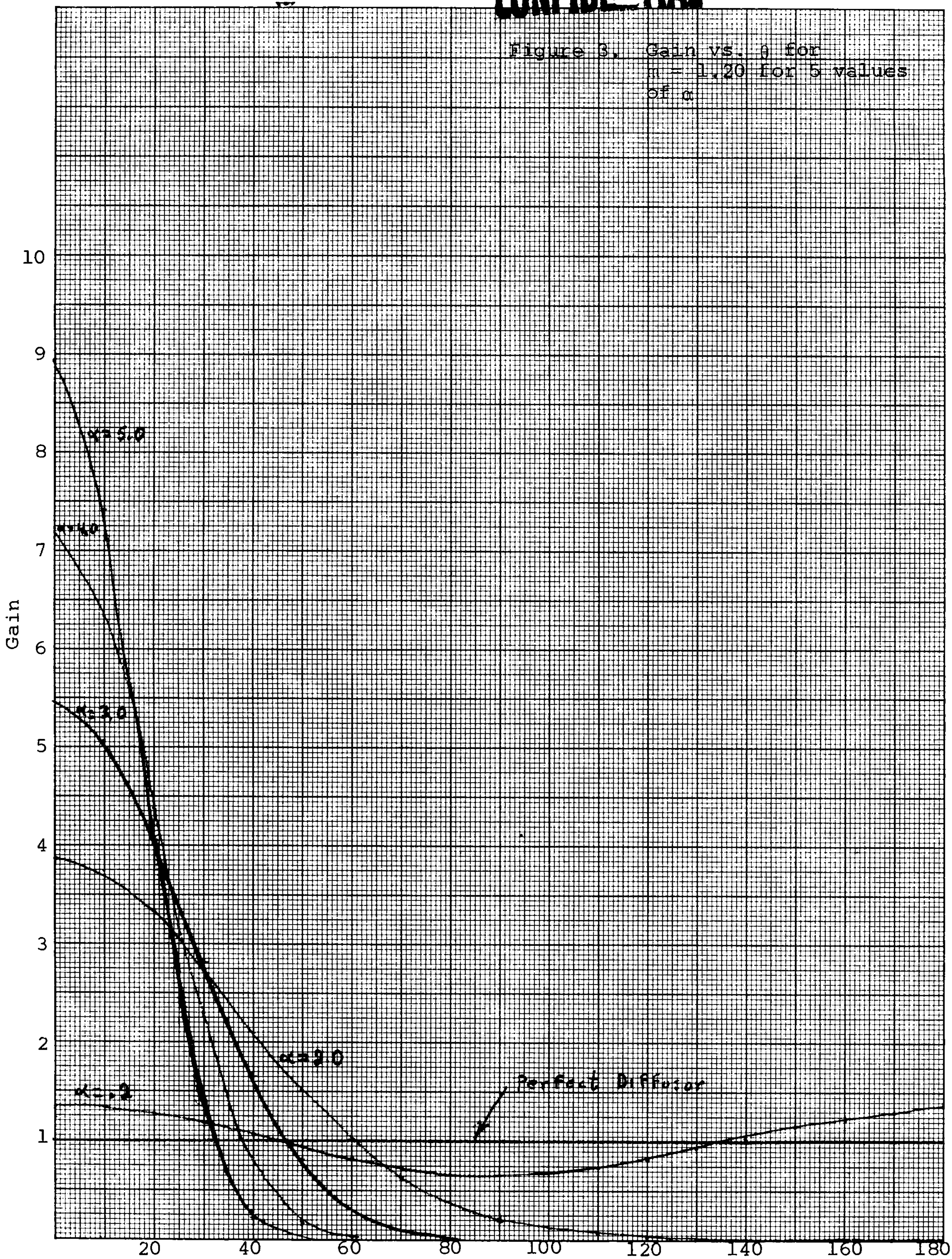

Figure 3. Gain vs. θ for m = 1.20 for 5 values of α
α=5.0
α=4.0
α=3.0
α=2.0
α=.2
Perfect Diffusor
Gain
10
9
8
7
6
5
4
3
2
1
20
40
60
80
100
120
140
160
180

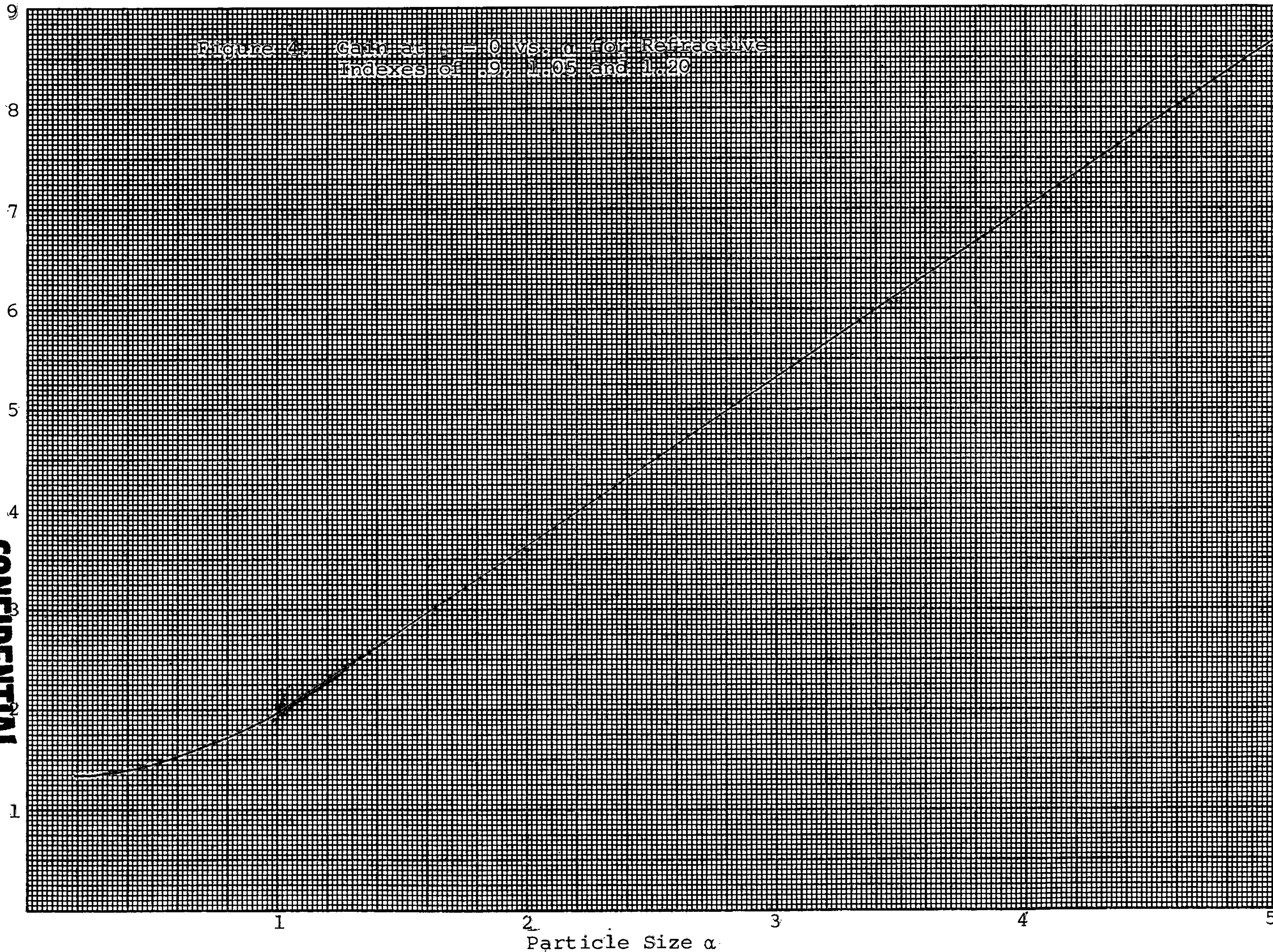

Figure 4. Gain at θ = 0 vs. α for Refractive Indexes of .9, 1.05 and 1.20

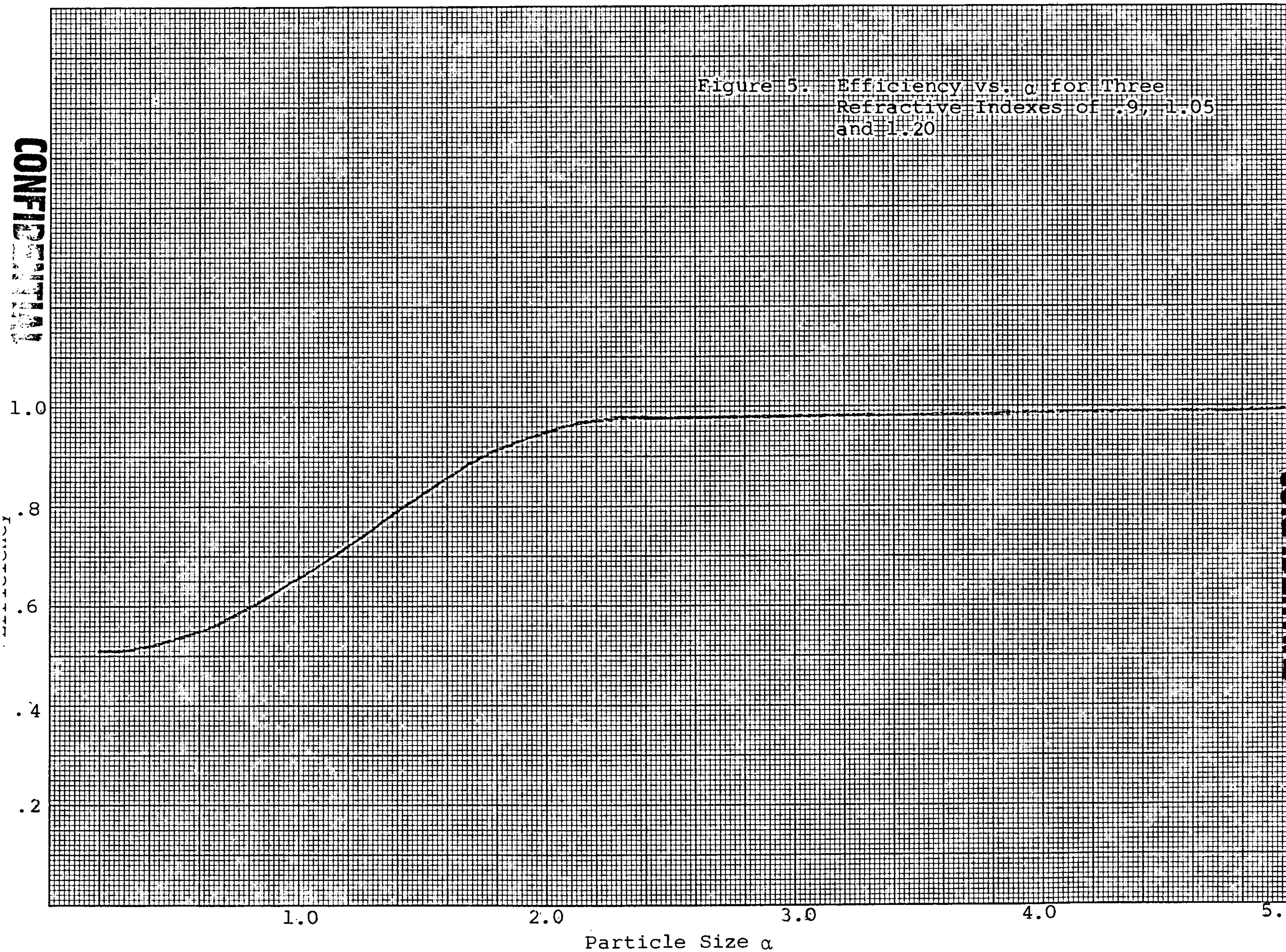

Figure 5. Efficiency vs. α for Three Refractive Indexes of .9, 1.05 and 1.20

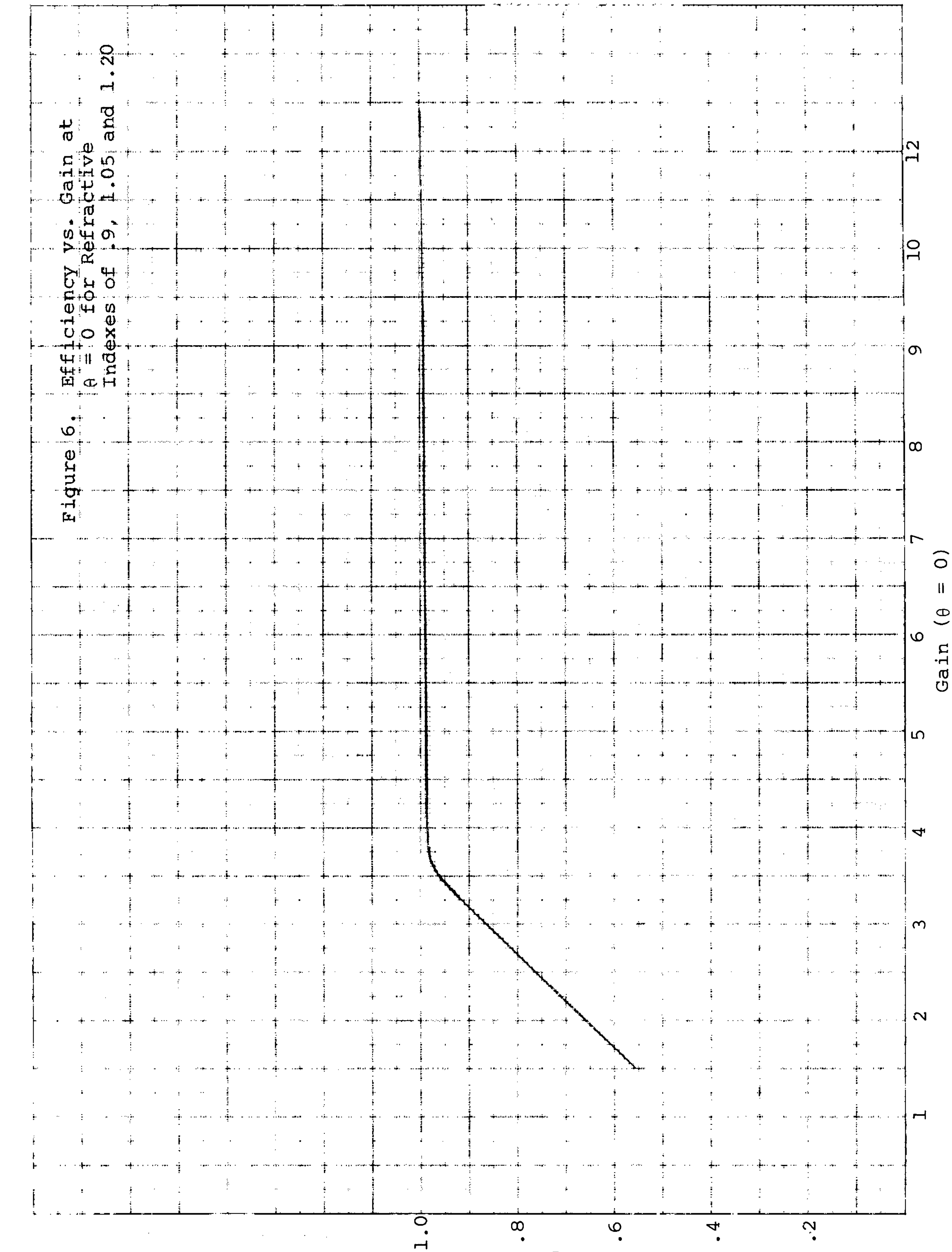

Figure 6. Efficiency vs. Gain at $\theta = 0$ for Refractive Indexes of .9, 1.05 and 1.20

efficiency vs. gain, fall very close together. It is interesting that there is no significant change in the efficiency beyond $\alpha = 2.0$ or a gain of 4. Here efficiency, EFF, is defined as the ratio of the intensity integrated over the forward hemisphere to the total incident intensity, i. e.,

$$EFF = \frac{\int_{\pi/2}^{\pi} I(\theta)\,db}{\int_{0}^{\pi} I(\theta)\,db} \qquad (1)$$

It should be recalled that θ is the angle measured between the direction of propagation of the scattered light and the reversed direction of propagation of the incident beam. The term gain, refers to the ratio

$$\text{Gain} = I(\theta)/I_i(\theta) \qquad (2)$$

where $I(\theta)$ is the scattered intensity from any given material and $I_i(\theta)$ is the intensity which would have been measured, at the same angle, had the material been an isotropic radiator, i. e., one which radiates uniformly in all directions.

GAIN

If the similarity of these curves hold for refractive indexes from .8 to 1.33 for the values of α of interest, then the refractive index cannot be considered a major design parameter like particle size. Thus, if this is true, only particle size will be significant for determining factors such as efficiency, gain at $\theta = 0$, and the shape of the scattering function. If this is substantiated by further studies, then this will considerably simplify some of the theoretical work.

Practically, however, it is virtually impossible to fabricate a screen material with a single particle size, as there will always be a finite range of particle sizes.

Therefore the problem becomes one of selecting a mean particle size and hopefully the distribution of sizes about it. Also because of the greater variety of scattering characteristics it may be more desirable to change the particle size distribution rather than the mean size of the particles or maybe both.

Let $f(\alpha_o - \alpha)$ be the size distribution about a mean size α_o, and $I(\theta)$ be the angular scattering function; then the angular scattering function $I(\alpha_o, \theta)$ for a distribution of particle sizes is,

$$I(\alpha_o, \theta) = \int_{-\infty}^{\infty} F(\alpha_o - \alpha) I(\alpha, \theta) d\alpha \qquad (3)$$

where $f(\alpha_o - \alpha)$ is normalized so that

$$\int_{-\infty}^{\infty} F(\alpha_o - \alpha) d\alpha = 1 \qquad (4)$$

At present a computer program is being written to do this type of analysis. Results will be reported next period. Also next period, scattering data for refractive indexes of .8, 1.10, 1.15, and 1.33 will be computed and compared with the data already obtained and reported.

A significant aspect of this work relating to the amount of light trapped in the glass by total internal reflection and the modification of the scattering function by refraction, have not been mentioned. The scattering functions of Figures 1 through 3 are valid only inside the scattering medium. This is because, in general, there will be a medium of different refractive index around the screen. Thus the light emerging from the screen will be refracted at this air-glass interface. The correspondence between θ, the angle inside the medium, and θ' outside the medium, is given by

$$\theta' = \sin^{-1} (n \sin \theta) \tag{5}$$

where n is the relative index of refraction between the matrix material of the screen and the surrounding medium. This refraction of the scattered light acts to broaden the scattering function which helps to make the screen more uniformly illuminated. At the same time we reach an angle beyond which all the scattered light is totally internally reflected. This critical angle, θ_c, is given by

$$\theta_c = \sin^{-1} \left(\frac{1}{n}\right) \tag{6}$$

which for n = 1.5 gives θ_c as 42 degrees. This means the light in the scattering function from 0° to 42° will be refracted by the screen and cover a 90° angle. All the light from 42° to 138° will be trapped in the screen until it is scattered at an angle less than θ_c which will allow it to pass out of the screen. In general the fraction of light trapped, I_t, is

$$I_t(\alpha) = \frac{\int_{\theta_c}^{\pi-\theta_c} I(\theta)d\theta}{\int_0^{\pi} I(\theta)d\theta} \tag{7}$$

It can be said that this light carries no information, as it does not convey an image which is in register with most of the light passing through the front surface of the screen. It, in essence, contributes a dc level of illumination to the screen, thereby reducing the contrast of all the information displayed.

Fortunately only one half of this passes through the front of the screen toward the viewers, but it is still a major factor in degrading the projected image. The efficiency, EFF., i. e., the usable fraction of light coming through the screen, is

$$\mathrm{EFF}(\alpha) = \frac{\int_{\pi-\theta_c}^{\pi} I(\theta)d\theta)}{\int_{0}^{\pi} I(\theta)d\theta} \qquad (8)$$

Because this integral extends only to θ_c and not to π, the efficiencies given in the previous figures will be too large, particularly for the smaller values of α. Finally the fraction of the light backscattered, I_b, is

$$I_b(\alpha) = \frac{\int_{0}^{\theta_c} I(\theta)d\theta}{\int_{0}^{\pi} I(\theta)d\theta} \qquad (9)$$

The obvious solution to the problem is to use particles which are larger than 5 microns which have correspondingly higher gains. By utilizing the fefraction property of the air-glass interface of the screen, acceptable angular gain characteristics can be obtained. A complete analysis of this, along with data on larger particle sizes, will be undertaken next period.

It should be noted that although the scattering functions we have derived assume that collimated light is incident on the sample, this in no way invalidates the data when it is applied to a general illumination problem. Figure 7 shows why this is true.

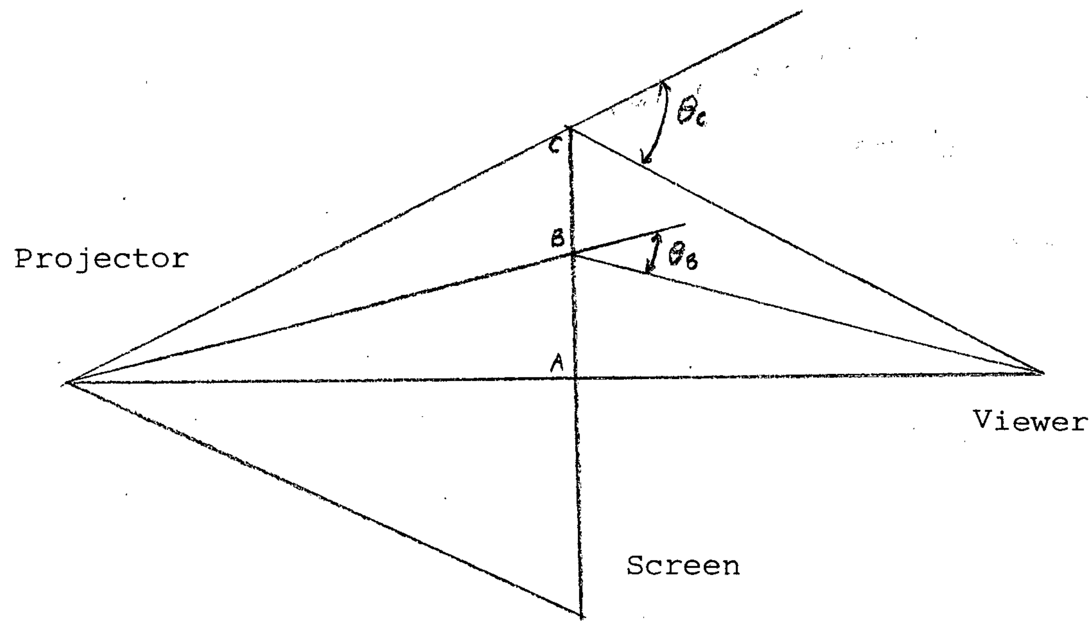

Figure 7. Geometry of a Rear Projection Display System

To determine the relative brightness between the three points A, B and C on the screen, three data from the scattering function curve are needed. The brightness of C relative to B is just, $I(\theta_C)/I(\theta_B)$, or of B relative to A is $I(\theta_B)/I(0)$. Values of $I(\theta_C)$, $I(\theta_B)$, and $I(\theta_A)$ are obtained directly from the scattering function data. The angles θ_B and θ_C are called bend angles and are determined by screen size, projection and viewing distance. The uniformity of illumination of the screen is therefore determined by bend angles and the scattering function.

II. CGW Materials

A trip to our facilities in Corning, New York, was made this period. Many technical personnel were consulted concerning the initiation of the third phase of our program which starts in April. This next phase is concerned with combining Corning's materials technology with specific materials requirements, generated during the theoretical phase of the program, to fabricate improved screens for rear projection viewing. Several different classes of materials, each with its own unique properties, will be separately investigated. The details of this program are presently being worked out and will be used as Phase III objectives.

A. Hollow Fibers

One of the advantages of using hollow fibers as a rear projection screen material is their ability to accept a large angular bundle of light, also they can be manufactured much easier than the cladded solid-core fibers, thereby making them less expensive.

Unfortunately, a large acceptance angle does not ensure a large exit angle. The number of reflections K is related to the length-to-width ratio r of fibers and the angle of incidence θ measured from the axis of the fiber, by

$$K = r \tan \theta \qquad (10)$$

The fraction of light transmitted, I/I_o is determined by K and the reflectivity R.

$$I/I_o = R^K \qquad (11)$$

A typical value of r might be 300 which corresponds to an inside diameter of 15 microns and a length of 5 mm. Clearly, K grows very fast because of the large value of r. Therefore, R must be very very near unity. Unfortunately metals do not have such reflectivities. Table 1 gives some typical values of the reflectivity for a few common materials(1).

Table 1. Reflection Coefficients of Surfaces for "Incandescent" Light

Material	Nature of Surface	Coefficient	Authority
Aluminum, "Alsak"	Diffusing	0.77-0.81	3
"Alzak"	Specular	0.79-0.83	3
on Glass	First Surface	0.82-0.86	4
Polished	Specular	0.69	3
Black Paper	Diffusing	0.05-0.06	4
Chromium	Specular	0.62	4
Copper	Specular	0.63	4
Gold	Specular	0.75	1
Magnesium Oxide	Diffusing	0.98	5
Nickel	Specular	0.62-0.64	1.3
Platinum	Specular	0.62	1
Porcelain Enamel	Glossy	0.76-0.79	3
Porcelain Enamel	Ground	0.81	3
Porcelain Enamel	Matt.	0.72-0.76	3
Silver	Polished	0.93	1
Silvered Glass	Second Surface	0.88-0.93	3
Snow	Diffusing	0.93	2
Steel	Specular	0.55	1
Stellite	Specular	0.58-0.65	4

(1) Hagen and Rubens. (2) Nutting, Jones, and Elliot. (3) J. E. Bock. (4) Frank Benford. (5) J. L. Michaelson.

For the data in Figure 9, a value of R = .93 (silver) was assumed; two curves, one for r = 60 and another for r = 300, are plotted. This clearly shows the consequences of R not being near unity, i. e., an extremely small "effective" acceptance angle results. For this reason a more careful evaluation of the feasibility of using hollow fiber tubes in rear projection screens is presently being made.

B. Other Materials and Approaches

Although much work has been done covering the more conventional type of rear projection screens, other approaches are also being considered. A novel screen idea has been patented by A. H. J. De Lassus St. Genies[2]. The screen consists of a thin layer of surfaces inclined at 45° to the surface of the screen. One side of all the surfaces is highly reflective and the other is coated with a light-scattering material, Figure 8.

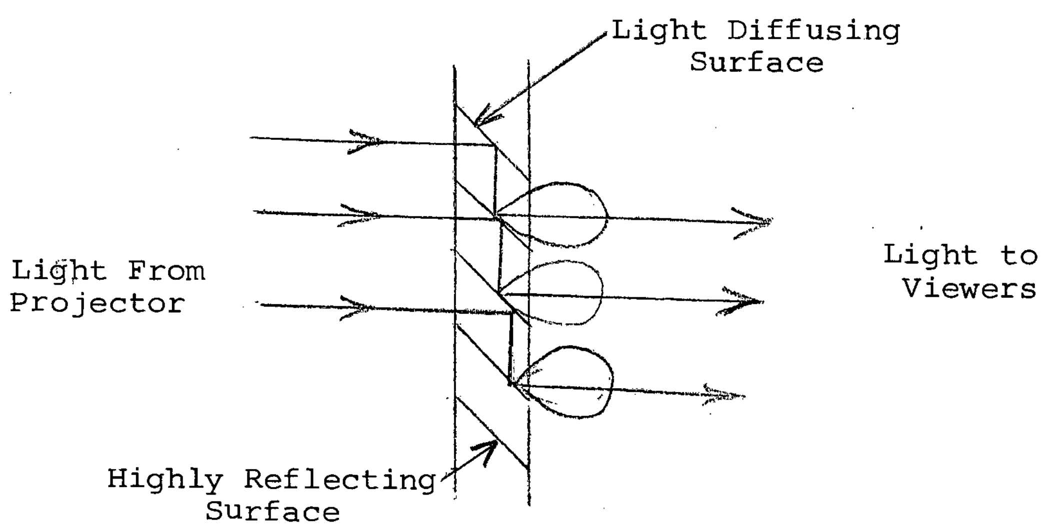

Figure 8. A Novel Screen Idea

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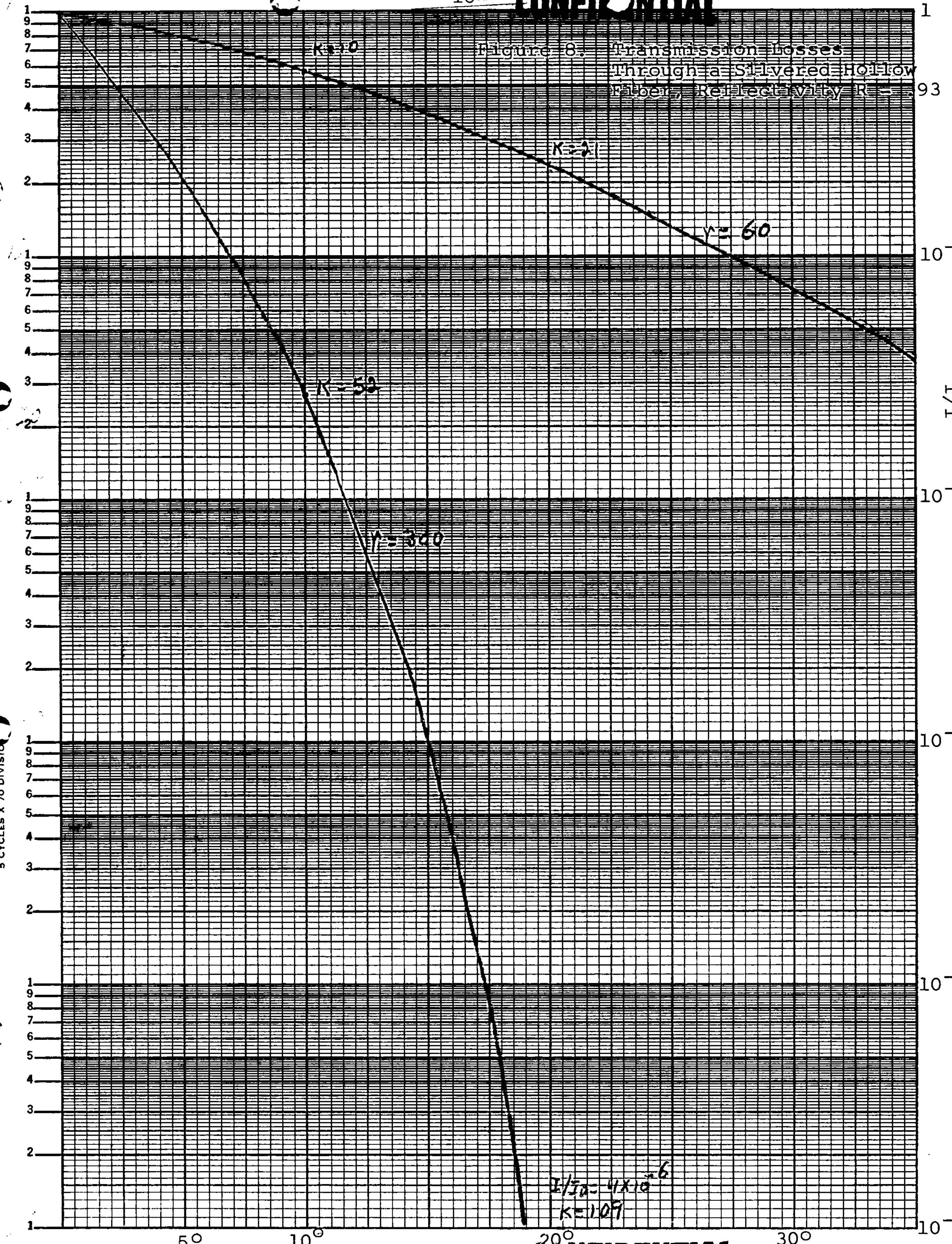

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Light incident from the back of the screen reflects from the first surfaces and is diffused into the viewing area by the second. The inclination of the surfaces can also be changed with increasing distance from the center of the screen which helps considerably in keeping it uniformly illuminated, i. e., it behaves much like a Fresnel screen. It also has the inherent high efficiencies of front projection screens and further the image detail is not disected by lenticules or fiber elements. It is insensitive to the ambient light level, and under normal viewing conditions no depth effects are observable because of the thinness of the screen.

The quality of such screens may or may not be suitable because of the line structure introduced at the many interfaces; this would also produce Moire effects. The fundamental idea is good and we will be fabricating some small samples for further study.

III. Instrumentation

A. Goniophotometer

All design work is complete with only the case remaining in the Machine Shop. The electronics and controls are being assembled and tested. The complete unit will be ready for use by the first of April.

B. Modulation Transfer Function Analyzer

Work on the sine-wave target generator is progressing on schedule. The special sine-wave target will be made using the optical arrangement shown in Figure 10. Modulation of the light beam will be accomplished by rotating a polarizer in a beam of

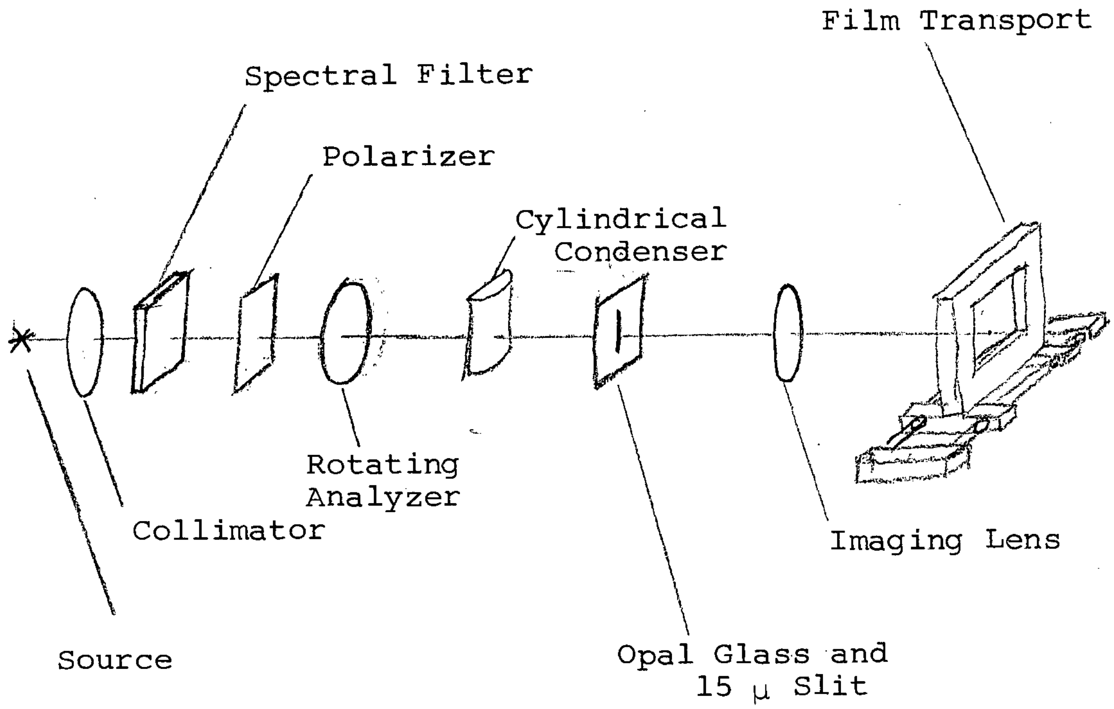

Figure 10. Optics for the Sine-Wave Target Generator

polarized light. When the polarizers are rotated so to be most opaque, their spectral transmittance changes, leaving a window in the blue. To prevent this from introducing non-linear effects, the spectral distribution of light from the source is limited by a spectral filter which peaks in the green portion of the spectrum. The spatial frequency R_x obtained in this way is given by

$$R_x = \frac{2F}{V} \tag{12}$$

where F is the frequency of rotation of the analyzer in cycles/sec. and V is the velocity of the film transport in mm/sec. The target pattern will have a continuously variable frequency from .2 to 10 cycles/mm, hence for V = 1 mm/sec requires F to vary from .1 to 5 revolutions/sec. This pattern will be demagnified 5 times in the MTF analyzer giving spatial frequencies from 1 to 50 cycles/mm.

The film transport with its controls will also be used as the transport in the MTF analyzer, its only moving part. Hence we are making a single piece of equipment do two jobs resulting in a considerable saving of time.

Already all of the major components are on order and the MTF analyzer and sine-wave mask generator are scheduled to be completed by the first of May.

References

(1) R. C. Weast, S. M. Selby, C. D. Hodgman, Handbook of Chemistry and Physics (The Chemical Rubber Co., Cleveland).

(2) A. H. J. De Lassus St. Genies, Projection Screen with Reflex Light-Transmission, U. S. Patent No. 2,931,269, April 5, 1960.